A Periodic Pattern-Aware and Runtime-Optimized Patterning Prediction Method for Mask Process Correction

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As process nodes shrink, improving computational efficiency and patterning accuracy of mask process correction (MPC) becomes essential due to the increasing complexity of mask patterns.[1] While Fast Fourier Transform (FFT) is widely used in mask process correction for pattern prediction (PP), it still struggles with the computational challenges of high-resolution PP, which is often required for complex mask patterns in advanced process nodes.[2] To address this issue, we propose a runtime-optimized and accurate patterning process estimation method for that leverages periodic pattern characteristics by accurately simulating energy contributions in original mask regions and approximating those in surrounding areas, expecting to reduce computation runtime while maintaining accuracy. In Fig. 1, (a) shows the internal energy from the original pattern's self-scattering (red circle region) and the external energy from the surrounding pattern's scattering (blue circle region). Below, Fig. 1 (b) depicts the cross-sectional view of corresponding energy contribution, separating the original energy contribution (red curve) and surrounding energy contribution (blue curve) along the position axis. Our proposed method is demonstrated in Fig. 1 (c) with (c1) illustrating BSL PP which adopts FFT as the convolution process, simultaneously accounts for the energy distribution of both the original and surrounding periodic mask areas. By employing high-resolution simulations, as illustrated in Fig. 1 (c3), it forms the foundation for subsequent checking and refinement processes (the arrow on the left). As the correction converges and the mask pattern is slightly modified, an approximate process (the arrow on the right) is applied, as shown in Fig. 1 (c2), where partial PP focuses on the internal energy contribution while reusing the previously computed surrounding energy contribution, significantly expecting to reduce computation time, as illustrated in Fig. 1 (c4). Although the partial model may introduce minor inaccuracies, these are resolved in the final checking and refinement step by reapplying BSL modeling to refine the corrections. Simulation results are presented in Fig. 2, which compares the contours and corrected masks obtained using the BSL and proposed methods for three different curvilinear patterns: (a) Via 1, (b) Via 2, and (c) Metal layers. The black lines represent the target patterns, while the red lines and the green dashed lines correspond to the corrected masks using BSL and the proposed methods and the purple lines and the blue dashed lines correspond to the contours using BSL and the proposed methods, respectively. These results demonstrate that the proposed method introduces only slight deviations in corrected mask variations compared to BSL. To further assess the accuracy of our approach in challenging correction scenarios, we magnified regions with high proximity effects, such as areas with dense environments or high curvature, aiming to better capture the errors most likely to occur due to approximation. The negligible differences between the two methods in these magnified regions highlight the fidelity and precision of our proposed method. Table 1 compares the proposed and regular methods in terms of accuracy and computational efficiency, including EPE_{max}, EPE_{mean}, EPE_{sigma}, runtime, and speed-up ratio. The maximum difference in EPE_{max} is approximately 0.08 nm (in Via 2), with errors in EPE_{mean} and EPE_{sigma} staying below 0.04 nm and 0.02 nm, as shown in the blue square demonstrating the comparable patterning accuracy. The proposed method achieves at least 11X speed-up, reaching up to 33X in Via 2 as shown in the red square presenting a high computational efficiency. These results highlight the proposed method's ability to significantly reduce runtime during iterations without compromising patterning accuracy, making it highly effective for process simulations. Moreover, analyzing the optimal timing for applying partial PP during correction convergence under BSL PP is ongoing.

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[1] S. Shin, B. Lee, S. Lee, E. bong Kim, M. Kim, J. Choi, S. Lee, Y. Sato, A. Syukri and I. Ono, in *Photomask Technology 2023*, 2023

[2] W. Yao, H. Zhao, C. Hou, W. Liu, H. Xu, X. Zhang, J. Xiao and J. Liu, in *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems 2022*, pp. 218

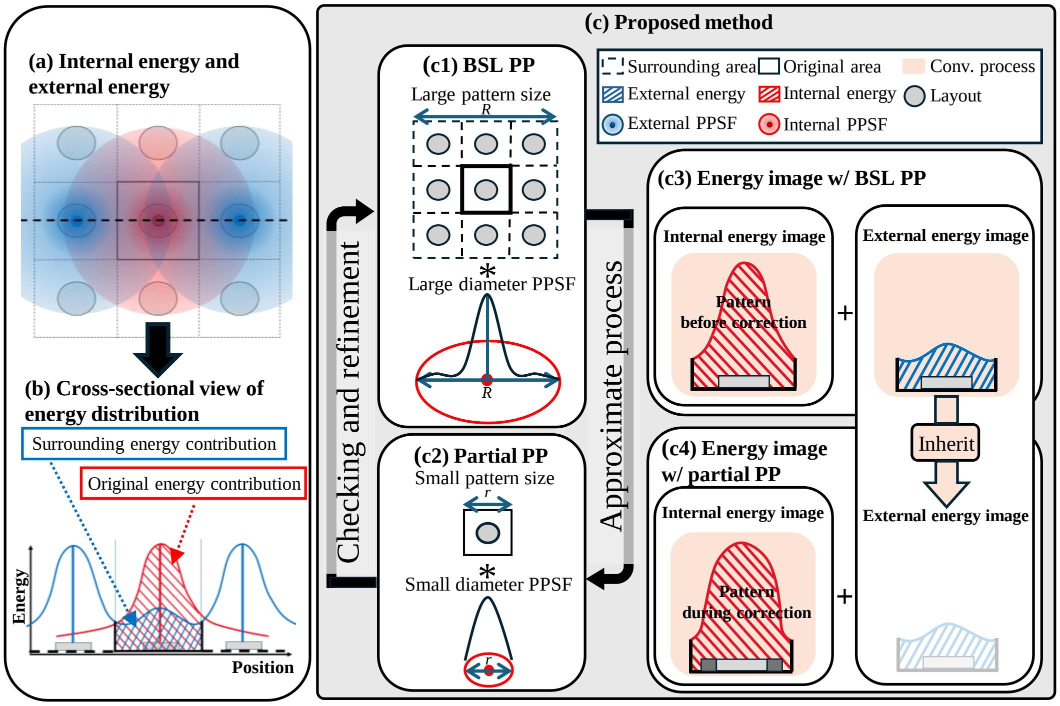

Fig. 1 Illustration of (a) the difference between the internal energy and external energy distribution, (b) the sectional view of energy distribution, and (c) the proposed method includes (c1) BSL PP, (c2) partial PP, (c3) the result of BSL PP and convolution region during data preparation. and (c4) the result of partial PP and convolution region during correction process.

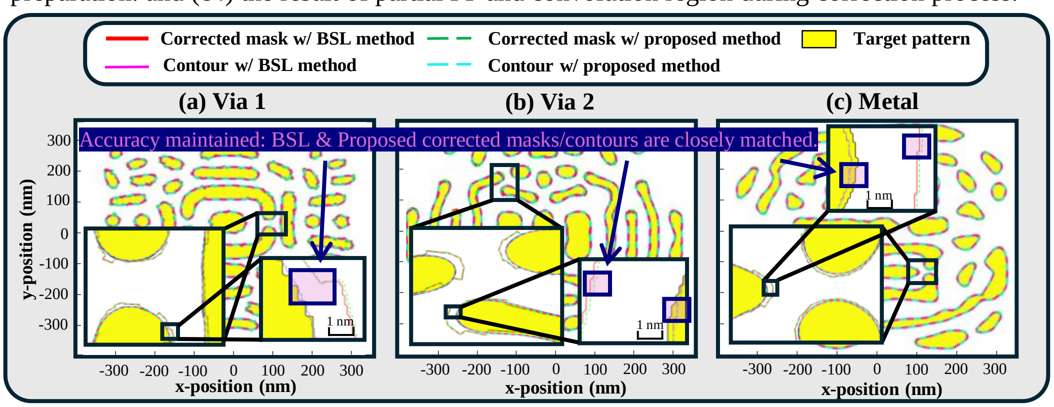

Fig. 2 Illustrations of three types of target pattern, corrected mask and contour used to evaluate the calculation performance with two different methods, including (a) Via 1, (b) Via 2 and (c) Metal. The contour differences of these three patterns between the two methods are very subtle, indicating that the error in the results calculated using these two methods is minimal.

Table 1 Comparison of EPE_{max}, EPE_{mean}, EPE_{sigma}, calculation time and speed up ratio between the regular method and the proposed method. The proposed method shows an at least 11X speed up in calculation time while maintaining comparable EPE error (maximum 0.08 nm error in EPE_{max}, 0.04 nm error in EPE_{mean} and 0.02 nm error in EPE_{sigma} between two method)

Pattern	Method	Accuracy			Runtime	Runtime Impro.
		EPE_{max} (nm)	EPE_{mean} (nm)	EPE_{sigma} (nm)	Time (sec)	Speed-up ratio (times)
Via 1	BSL	0.4000	0.0750	0.0747	1682	**14.88**
	Proposed	0.4000	0.1118	0.0953	**113**	
Via 2	BSL	0.3162	0.0579	0.0572	1227	**33.16**
	Proposed	0.4000	0.0729	0.0682	**37**	
Metal	BSL	0.3000	0.0740	0.0730	956	**11.12**
	Proposed	0.3000	0.0745	0.0740	**86**	